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Multi-objective low voltage grid tariff setting

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Abstract

The design of low voltage (LV) grid tariffs can be constrained by several political objectives for the electricity sector, such as energy conservation or an increase of local generation. This leads to trade-offs between these objectives. In this paper, a multi-objective model is proposed, to address this task in a European context. The model calculates Pareto-optimal shares of the capacity and energy components for different sets of decision variables. In a case study, the model is implemented for a number of tariff structures such as a flat tariff and a time of use (ToU) tariff. Results show the trade-off between the objectives. They also show the impact of rising levels of local generation and of a variation in the tariff structure. These case study results outline the importance to formalize high level political objectives and to include them in the tariff design process.

I. Introduction

Grid tariffs for electricity grids are needed to generate the revenue which is needed by the grid operator for a sustainable grid operation. Additionally, grid tariffs, as part of the retail price for electricity, are seen as key to achieve energy policy objectives, such as a successful integration of renewable energies and distributed flexibilities into the electricity grid [1], [2].

A major objective for grid tariffs is cost reflectivity [1]. Under a cost-reflective tariff, a grid user pays grid fees that reflect the user's contribution to the grid costs [3]. Reflectivity has two sub-aspects: The first aspect is to give an economic signal to the users [4]. Given an appropriate signal, users reacting to this signal reduce grid costs, by reacting in a way that reduces their own grid fees. The second aspect is the cross-subsidization between the grid users [5]. The better the grid fee reflects the costs that an individual user caused to the system, the less the users cross-subsidize each other. In this way, a reflective tariff contributes to economic efficient operation of the grid and ensures that users pay an appropriate grid fee.

Yet, reflective tariffs might lack social acceptability or contradict regulation, requiring adjustments for further objectives such as [1], [6], [7]:

- Affordable retail prices for electricity
- Reduction of energy consumption
- Increase in renewable generation
- Reduction of CO_2 emissions

To these objectives, tariffs have to be aligned with [2], [7].

These new objectives make the process of tariff design increasingly complex by adding an increasing number of trade-offs: A classical one is the trade-off between reflectivity and simplicity: The tariff should be as reflective as possible while being as simple as needed [3]. Local generation, for instance through PV, can add a further trade-off: Local generation can increase the cross-subsidization between users. Under schemes such as net-metering or net-billing, users with local generation can reduce the grid fees they pay [8]. Yet, they do not necessarily reduce the costs they cause to the system. This leads to a lack of revenues for the grid operator that has to be covered by all users [9], [10]. A reflective tariff could address this. But, the reduced grid fee is also part of the business case for local generation. This business case could suffer under a reflective tariff. This would contradict the policy objective to increase renewable generation. A further trade-off can be observed for the reduction of energy consumption: [5] have calculated that, for the low-voltage grid, costs are mainly related to the system peak load. A reflective tariff could address this by emphasizing the capacity component. Yet, this would reduce the price per unit of energy and therefore the incentive to reduce consumption.

Tariff design, thus, increasingly means to set a tariff which recovers costs and is reflective on the one hand but also to assess the impact on energy policy objectives on the other hand.

In the literature, several proposals for grid tariffs can be found that address the objective of reflectivity [3], [11]–[15]. Specific distribution proposals can be found in [4], [5], [16]–[18]. These tariff proposals include so-called marginal-cost based tariffs and embedded-cost based tariffs [12]. Except for [5], all proposals that are listed cover marginal-cost based tariffs.

For the LV grid, however, embedded-cost based tariffs are considered as the most relevant tariffs [19]. These tariffs are especially relevant with regard to cost recovery. Yet, concerning the research on these tariffs, a number of shortcomings can be identified. A first aspect is the cost reflectivity of such tariffs. Here, [19] identify a general lack of research. A second aspect is the challenge to integrate the new energy policy objectives, and the described, resulting trade-offs, into the tariff setting process. No reference addressing this aspect was found in the literature. For the tariff-setting process, thus, parties like the regulator lack a tool to assess either to which extend a single tariff proposal fulfills all the contradicting objectives of energy policy, or, in case of competing tariffs, which tariff offers the best compromise, with respect to these objectives.

To address this concern in a systematic way and to compare the efficiency of existing tariff structure, we propose herewith a framework to design, and assess, use-of-grid (UoG) tariffs. This framework is more specifically suited for LV grid users, considering a set of objectives with diverse nature using a multi-objective model. One of these objectives is cost reflectivity. The focus of this paper, with respect to this reflectivity, is to quantify the degree of cross-subsidization between the users. The tariff, calculated by using the model in this paper, can be, then, used as an input to predict the user reaction, as described in [20]. This allows assessing the economic signal provided by a tariff.

The paper is organized as follows: Section II gives an overview of the retail price composition. In section III, the framework model is described including the decision variables, the objectives and the optimization problem. The model is illustrated in a case study in section IV. Conclusions can be found in section V.

II. COMPOSITION OF THE RETAIL PRICE

In this work, we focus on the grid tariff as part of the retail price, the signal faced by most LV grid users. In general, retail prices are set by the supplier, as depicted in Figure 1. This price is usually set to

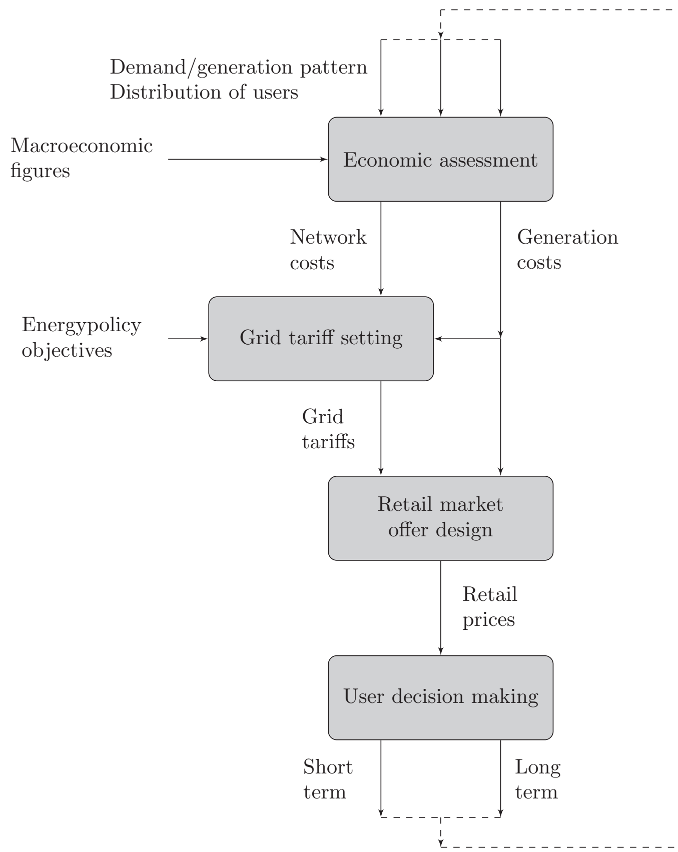

Fig. 1. Context of the grid tariff

cover three cost components: C_{CS} for energy sourcing and commercial costs, C_{N} for grid costs, and C_{TL} for taxes and levies. The relative significance and definition of each component differs strongly from one region to another [21]. The annual amount C_{Total} invoiced by the supplier to the user i corresponds to

$$C^i_{\text{Total}} = C^i_{\text{CS}} + C^i_{\text{N}} + C^i_{\text{TL}} \tag{1}$$

For the grid tariff, the focus of this paper is on the cross-subsidy between the users. With regard to economic signaling, however, it is assumed in this paper that such signals would be integrated into the respective component. Grid related signals would, thus, be sent out by the grid operator through the grid tariff and, then, be integrated by the retailer into the grid component. This is in line with the required separation between grid operators and retailers [1].

A. Energy sourcing and commercial costs

The component for energy sourcing and commercial costs is designed ex-ante by the supplier based on predictions about the users' behavior and its sourcing costs. The resulting price can be flat or differentiated for different time-slots. In this work it is assumed as:

$$C_{\text{CS}}^{i} = \sum_{p=1}^{P} e_p \cdot E_p^i \tag{2}$$

where e is a specific commodity price during period p, E the energy taken off during p and p denotes periods of different prices, e.g. peak and off-peak times. This commodity component can be used by the retailer or an aggregator to send out economic signals, for instance related to the wholesale market.

B. Grid component

For most LV grid users, there is a specific grid component in the retail price based on the grid tariff of the grid operator. As outlined in the introduction, this grid tariff has to recover the costs of grid operation (investment, ancillary services, reactive power, etc.) in a reflective way.

The costs that shall be recovered are usually allocated to three different tariff components:

- A (one-off) tariff for the connection to the grid.
- A tariff independent from the metered load pattern.
- A use-of-grid (UoG) tariff depending on the metered load pattern. This can be, for instance, energy based or capacity based.

This allocation is in fact the problem of pricing an option to use the grid. Parts of the costs that are reflected by the UoG tariff are known only ex-post. Also, the reflective allocation of fixed costs depend on the usage of the system which is not known upfront. A truly reflective tariff had to be designed and charged after these costs and the grid users' contribution to the costs are known. Yet, grid users and regulators usually require ex-ante tariffs, for instance for the next year or the next day. Such a tariff design can only reflect the predicted costs of using the grid. In this work, the composition of the UoG fee is assumed as:

$$
\begin{aligned}
C_N^i = \sum_{j=1}^{J} (c_{\text{Off},j}^{\text{En}} \cdot E_{\text{Off},j}^i + c_{\text{Inj},j}^{\text{En}} \cdot E_{\text{Inj},j}^i \\
+ c_{\text{Off},j}^{\text{Cap}} \cdot P_{\text{Off},j}^i + c_{\text{Inj},j}^{\text{Cap}} \cdot P_{\text{Inj},j}^i) + d_{\text{Independent}}
\end{aligned}
\tag{3}
$$

c denotes a specific tariff proportional to energy E taken off or injected and capacity P used for take-off or injection during period j. Grid fees are calculated for customer i. For every component J different time-slots can exist. A possibility is to have J = 2 with j = 1 denoting peak time and j = 2 denoting off-peak time. Component $d_{\text{Independent}}$ denotes a fee component that is not proportional to the aforementioned variables.

To meter, or to cap, the used capacity and to meter the grid use during different time-slots, it is assumed that users are equipped with electronic/smart meters.

C. Taxes and levies

A major component of taxes is the value added tax (VAT, sales tax). This tax is calculated as a percentage of the net bill. The rate differs within the EU. Levies are often related to green energy schemes. Taxes and levies can be proportional ($c_{\text{Tax, prop.}}$) or independent ($C_{\text{TL,net}}$). Given this, (1) is reformulated as:

$$
C_{\text{Total}}^i = (C_{\text{CS,net}}^i + C_{\text{N,net}}^i + C_{\text{TL,net}}^i) \cdot c_{\text{Tax, prop.}} \tag{4}
$$

III. Multi-objective tariff setting framework

In this paper, a multi-objective framework is proposed. As will be outlined in the remainder of this section, this framework uses a number of objectives which are combined to a single objective by weighing the individual objectives. Then, the single-objective function is minimized to derive a set of energy components and capacity components which are optimal for a predefined tariff structure, and one set of weights for the individual objectives. For this, general political objectives for the electricity sector have to be translated into tangible objectives that can be formalized. In this section, at first the optimization variables are defined. Then, objectives and constraints which are considered are described qualitatively and are formalized. Finally, a single-objective optimization problem is proposed.

The objectives are the result of a selection process. There are other possible objectives and other possible ways to formalize them. Also, some objectives could be defined as constraints and vice-versa.

A. Decision variables

The decision variables are divided into design variables and control variables [22]. The design variables are the output of the optimization while the control variables are set upfront. The design variables are the factors $c^{\text{En}}_{\text{Off},j}$, $c^{\text{En}}_{\text{Inj},j}$, $c^{\text{Cap}}_{\text{Off},j}$ and $c^{\text{Cap}}_{\text{Inj},j}$ from (3) for the respective time-slots.

The control variables are:

- Number and length of the j time-slots in (3). This can be, for instance, j = 1 denoting peak time every day of the year from 6 - 22 hours and j = 2 denoting the remaining time.
- The existence of injection components.
- The number of measurements for determining the capacity values $P_{\text{Off},j}$ and $P_{\text{Inj},j}$ also in (3).
- The value of an independent factor $d_{\text{Independent}}$.

B. Objectives

1) Cost reflectivity: The importance of cost reflectivity is outlined in the introduction. As noted, the aspect of reflectivity that is addressed in this work is the degree of cross-subsidization between the users.

Since costs related to grid use are difficult to measure, grid use itself can act as a proxy for the costs that a user causes [15]. Main links between grid use and grid costs are the users' contribution to the local system peak load, the users' contribution to losses and the potential use related to a connection [2], [5], [23]–[25]. As outlined, this calculation is based on predicted use and costs, leading to a predicted reflectivity.

In this work, it is assumed that a user's contribution to the peak load is the user's respective load at the moment of the system peak. There can be a positive and a negative peak. Users can also contribute to an increase or a decrease of the system peak. This has to be considered:

$$U^i_{\text{Peak}} = \gamma(P^i_{\text{T+}}/P_{\text{T+}}) - (1-\gamma)(P^i_{\text{T-}}/P_{\text{T-}}) \tag{5}$$

P_{T} denotes the positive(+) and negative(-)[1] system peak load. P^i_{T} is the load of user i at the moment of the respective system peak. The weight γ describes the relevance of positive and negative system peak. γ can be set by the user of the framework, based, for instance, on the ratio of positive peak load and negative peak load.

In this work, it is assumed that losses are allocated using the so called pro-rata method [26]. This method allocates losses to a user proportional to the user's contribution to system-load. Besides being simple, this method has the advantage of being independent from location (see section III-C3). By allowing positive and negative contributions to system-load, it is also considered whether a user increases or decreases losses. Based on this, the contribution to losses can be defined as:

$$U^i_{\text{Loss}} = \sum_{t=1}^{T} \big((P^i_t/P_t) \cdot (E_{\text{Loss},t}/E_{\text{Loss}})\big) \tag{6}$$

P_t denotes the system-load and P^i_t the load for user i in time-step t. E_{Loss} denotes the lost energy.

A part of the use can also be independent from these two parameters. This can be, for instance, an

[1]If a negative load occurs.

equal factor for all I users.

$$U^i_{\text{Ind}} = 1/I \tag{7}$$

Based on the initial assumptions about the grid use, the total use is, here, defined to be the weighted sum of these three elements. The resulting grid fee should be proportional to this use. The sum of all fees have to be equal to the revenue target (see section III-C1). Therefore, the expected fees $C^i_{\text{N, Exp.}}$ for user i can be determined by multiplying the weighted use of user i with the revenue target. The weight factors α_1 - α_3 are arbitrarily chosen based on the assumed composition of total grid costs. This composition can be derived, for instance, from [2].

$$C^i_{\text{N, Exp.}} = \alpha_1 \cdot U^i_{\text{Peak}} + \alpha_2 \cdot U^i_{\text{Loss}} + \alpha_3 \cdot U^i_{\text{Ind}} \tag{8}$$

$$\alpha_1 + \alpha_2 + \alpha_3 = R_{\text{Grid}} \tag{9}$$

where R_{Grid} is the revenue target of the grid operator. This gives a linear relation between expected fees and use.

The actual fees are the fees according to (3). The deviation from reflectivity V_{Refl} is formalized as the norm of the deviation between expected fees $C^i_{\text{N, Exp.}}$ and actual fees C_{N} over all grid users.

$$V_{\text{Refl}} = \sum_{i=1}^{I} \sqrt{(C^i_{\text{N, Exp.}} - C^i_{\text{N}})^2} \tag{10}$$

This way to describe the cross-subsidization is similar to [20]. In contrast to [20], however, at this point, cross-subsidization is minimized through the tariff design and not just quantified.

2) Energy conservation: Energy conservation is mentioned as a major objective of policy making. Schemes exist which support increasing energy efficiency and reducing consumption. A pure energy based tariff supports such efforts while a pure capacity based grid tariff might counteract them. It is proposed here to focus on reductions in the consumption of an electric heating system (e.g. heat-pump) related to isolation measures.

To estimate the effect of the isolation, it is proposed to estimate an increase in temperature related to the isolation which leads to less use of the heating. This results in two different load profiles, one initial $\boldsymbol{P}^i_{\mathrm{T}^0}$ and one for the increased temperature $\boldsymbol{P}^i_{\mathrm{T}^0+\mathrm{X}}$. These profiles lead to different grid fees:

$$C^i_{\mathrm{N,T}^0} = C^i_{\mathrm{N}}(\boldsymbol{P}^i_{\mathrm{T}^0}) \qquad C^i_{\mathrm{N,T}^0+\mathrm{X}} = C^i_{\mathrm{N}}(\boldsymbol{P}^i_{\mathrm{T}^0+\mathrm{X}}) \tag{11}$$

The gain related to the isolation measure V_{Gain} is the difference between the two grid fees over all customers:

$$V_{\mathrm{Gain}} = \sum_{i=1}^{I}(C^i_{\mathrm{N,T}^0}) - \sum_{i=1}^{I}(C^i_{\mathrm{N,T}^0+\mathrm{X}}) \tag{12}$$

3) Risk of the bill: There is a risk or unpredictability related to the final electricity bill. This can be the result of an unpredictable retail price. It can also be a result of actual user behavior. This behavior is not fully predictable. For instance, the electric heating can just switch on, while the user is using the stove and the kettle, or the user uses more heating because the winter is colder than expected. This can lead to deviations between the expected electricity bill and the actual bill. The extent of this deviation depends to some extent on the tariff design. Tariffs in this paper are assumed to be known upfront, so there is no additional uncertainty from the tariff. Yet, changing the share of energy part and capacity part can influence the deviation of the bill. To protect users, the tariff has to be designed in a way that deviations are limited. Controlling the risk contributes to the objective of social acceptability.

For the considered grid tariffs, the actual bill $C_{\mathrm{Total,actual}}$ is a result of the actual load pattern $\boldsymbol{P}_{\mathrm{actual}}$ and the resulting grid fees $C_{\mathrm{N,actual}}$:

$$C^i_{\mathrm{Total,actual}} = C^i_{\mathrm{Total}}(C^i_{\mathrm{N}}(\boldsymbol{P}^i_{\mathrm{actual}})) \tag{13}$$

This is in contrast to the initially predicted bill C_{Total} resulting from the predicted pattern $\boldsymbol{P}$:

$$C^i_{\mathrm{Total}} = C^i_{\mathrm{Total}}(C^i_{\mathrm{N}}(\boldsymbol{P}^i)) \tag{14}$$

The average risk of the bill V_{Risk} due to variation of the load profile is calculated based on the actual bill

$C_{\text{Total,actual}}$ and the predicted bill C_{Total} as:

$$V_{\text{Risk}} = \sum_{i=1}^{I} \left(\frac{\sqrt{(C^i_{\text{Total, actual}} - C^i_{\text{Total}})^2}}{C^i_{\text{Total}}} \right) \tag{15}$$

4) Balance between professional and residential users: Residential customers and small professional customers usually face the same grid tariff. Yet, they have a different load pattern as expressed by different standard load profiles (SLP). Tariff design can have different impacts on the average fees for these different groups. Finding a balance between such different user groups contributes to the policy objectives of social acceptability and affordable electricity for all users.

To estimate the impact of different grid tariffs on professional and residential users, it is proposed to define a representative load pattern ($\boldsymbol{P}^{\text{Pro}}_{\text{Avg}}$ and $\boldsymbol{P}^{\text{Res}}_{\text{Avg}}$) for both user groups. For these representative patterns, the grid fees are calculated.

$$C^{\text{Res}}_{\text{N}} = C_{\text{N}}(\boldsymbol{P}^{\text{Res}}_{\text{Avg}}) \qquad C^{\text{Pro}}_{\text{N}} = C_{\text{N}}(\boldsymbol{P}^{\text{Pro}}_{\text{Avg}}) \tag{16}$$

Now, it is assumed that the grid fees for professionals shall be in a certain pre-defined ratio to the fees for residential users. This can be expressed by the arbitrarily chosen scaling factor λ. The (unwanted) deviation of the grid fees for the two groups V_{RePr} can then be expressed as the norm of the difference between the grid fees.

$$V_{\text{RePr}} = \sqrt{(C^{\text{Res}}_{\text{N}} - \lambda C^{\text{Pro}}_{\text{N}})^2} \tag{17}$$

C. Constraints

The optimization is constrained by factors explained in this section. Depending on the objectives for the tariff setting, some constraints and objectives can be exchanged. For instance, a certain maximum or minimum gain from measures of energy conservation could be defined.

1) Cost recovery: Grid operation is a regulated business. In this system grid operators are entitled to generate revenues up to a limit set by the regulator. This limit is related to the costs of the grid operator. To fulfill the requirement of cost recovery, total grid fees in a planning period have to be equal to the revenues R_{Grid}, the grid operator is entitled to recover during the same period.

$$\sum_{i=1}^{I}(C_{\text{N}}^{i}) = R_{\text{Grid}} \tag{18}$$

2) Limited effect on distributed generation: Targets for renewable energy are mentioned as a political objective. A major building block is renewable generation on residential level. Investment will take place if there is a positive business case. This business case can be influenced by the grid tariff design. Grid tariffs should be set in a way that they at least not counteract the objectives. Local (PV-) generation, expressed as $\boldsymbol{P}_{\text{PVprofile}}$, leads to a different load profile $\boldsymbol{P}_{\text{PV}}$ which leads to different grid fees $C_{\text{N,PV}}$ for the PV operator.

$$\boldsymbol{P}_{\text{PV}}^{i} = \boldsymbol{P}^{i} + \boldsymbol{P}_{\text{PVprofile}} \tag{19}$$

$$C_{\text{N,PV}}^{i} = C_{\text{N}}^{i}(\boldsymbol{P}_{\text{PV}}^{i}) \tag{20}$$

The effect V_{PV} is the difference in grid fees with and without local generation.

$$V_{\text{PV}}^{i} = C_{\text{N,PV}}^{i} - C_{\text{N}}^{i} \tag{21}$$

This effect can be positive or negative, depending on the grid tariff. With respect to the objective to increase the share of renewable generation, the effect could be minimized, maximized or limited to a certain value. At this point, it is proposed to limit the effect on the grid fees:

$$V_{\text{PV}}^{i} \leq K_{\text{limit}}^{i} \tag{22}$$

K_{limit}^{i} is an arbitrarily chosen limit that ensures that tariff setting is in line with policy objectives concerning distributed generation. This constraint could be also defined as the objective to maximize the gain a PV operator has from installing and operating it.

3) Uniform tariff setting: In many European countries, regulation requires general tariff setting in the LV grid. This means that a certain tariff has to be available to all users of the respective grid operator. This also means that locational tariffs cannot be applied.

4) Simplicity: Simplicity is an important criterion of tariff setting. Yet, it is difficult to measure. It is proposed here to sum up the variation between consecutive tariff elements as a measure for complexity:

$$V_{\text{Sim}} = \frac{\sum_{j=1}^{J} \sqrt{(c_{\text{Off},j}^{\text{En}} - c_{\text{Off},j-1}^{\text{En}})^2}}{\sum_{j=1}^{J} c_{\text{Off, Avg}}^{\text{En}}} \tag{23}$$

The outcome would be a percentage value that indicates a relative cost of complexity. This measure includes the variation between elements and the number of elements. This last parameter is a relevant input factor, for instance, to determine tax complexity. The energy component is considered here as it is the most commonly used for time variation.

D. Optimization problem

The optimization problem is formulated as a single-objective optimization problem. The four objectives are linearly combined with weight factors w_1 - w_4. These weight factors have to sum up to 1 and can be arbitrarily chosen by the user of the framework depending on the weight assigned to each objective. This can be done based on political focus. An alternative is to use several weight combinations and pick the one with the most suitable results.

A problem of this linear combination is that the individual objectives are not directly comparable. The objectives have different units and the objective values have different orders of magnitude. Therefore, trade-offs between the objectives cannot be properly calculated. To make the objectives comparable, they can be normalized. For a normalized objective, not the absolute value is considered, but the relative deviation from the optimal value of the respective objective. A way to normalize the L objectives V_l is depicted in (24) [27].

$$V_{\hat{l}}^{\text{Norm}} = \frac{V_{\hat{l}}^{*} - V_{\hat{l}}^{\text{Min}}}{V_{\hat{l}}^{\text{Max}} - V_{\hat{l}}^{\text{Min}}} \tag{24}$$

$V_{\hat{l}}^{*}$ is the calculated value for a certain weight $w_{\hat{l}}$, $V_{\hat{l}}^{\text{Min}}$ is the minimum, or optimal, value and $V_{\hat{l}}^{\text{Max}}$ is the maximum, or worst, value for objective $\hat{l}$.

It is important that both $V_{\hat{l}}^{\text{Min}}$ and $V_{\hat{l}}^{\text{Max}}$ are elements of the solution-set of the combined objective function [27]. The optimal value $V_{\hat{l}}^{\text{Min}}$ for an individual objective can be obtained by minimizing[2] the objective $V_{\hat{l}}$ individually. This can be done by using a weight $w_{\hat{l}} = 1$. The resulting solution is an element of the solution-set of the combined objective function. Yet, the worst value $V_{\hat{l}}^{\text{Max}}$ cannot be found by maximizing[3] the objective $V_{\hat{l}}$ individually. This would be equal to using a weight $w_{\hat{l}} = -1$. The resulting solution is, thus, not an element of the solution-set of the combined objective function. Values for $V_{\hat{l}}$ which are part of this solution-set are values which are obtained if the other objectives are optimized individually by setting all other weights $w_{\{l|l\neq\hat{l}\}}$ to one. These values are used by the so-called pay-off table. As value $V_{\hat{l}}^{\text{Max}}$, the pay-off table uses for $V_{\hat{l}}$ the worst of those values for $V_{\hat{l}}$, which are obtained when optimizing the other objectives individually.

The optimization problem is, then, formulated as a single-objective optimization problem:

$$\begin{aligned} min: \quad & V_{\text{T}} = w_1 \cdot V_{\text{Refl}}^{\text{Norm}} - w_2 \cdot V_{\text{Gain}}^{\text{Norm}} + w_3 \cdot V_{\text{Risk}}^{\text{Norm}} + w_4 \cdot V_{\text{RePr}}^{\text{Norm}} \\ s.t.: \quad & (18), (22) \\ & w_1 + w_2 + w_3 + w_4 = 1 \end{aligned} \tag{25}$$

In this formulation V_{Gain} is maximized while the other three objectives are minimized.

Minimizing the objective function V_{T} leads to a solution for a certain set of weights $\hat{w}_1 - \hat{w}_4$. For each of these solutions, it has to be defined whether the solution is a global optimum, or whether it is just a local optimum [27], [28].

For the objective function V_{T}, all local optima are also global optima, due to the convexity of the function [28]. A non-negative linear combination of convex functions, as given in V_{T}, except for V_{Gain},

[2]Maximizing in case of objective V_{Gain}
[3]Minimizing in case of objective V_{Gain}

yields a convex function. For V_{Gain}, $-V_{\text{Gain}}$ has to be convex, thus. V_{Gain} is a linear function. Linear functions are convex and concave. Inversing a convex function yields a concave function and vice versa. As V_{Gain} is convex and concave, $-V_{\text{Gain}}$ is concave and convex. The three other objective functions are norms, which are convex. The normalization in (24) is a linear transformation, which does not change the convexity of the initial functions.

IV. Case study

A. Input

1) Grid users: For the calculation of the individual bills, a set of 60 individual residential load profiles, reflecting 60 grid users, is assumed. These are representatively calculated based on [29]. The resolution Δt of these profiles is 15 minutes. At this point, real electronic/smart meter data could provide a vitally important input factor.

To these load profiles, PV generation profiles are added to simulate local generation. Four scenarios for the addition of PV with different penetration rates are assumed. These rates are 0%, 25%, 50% and 100%. So in the 25% scenario, a PV profile is added to every 4th load profile. The base PV profile is the same for all users. This base profile is scaled for every user so that annual generation matches annual consumption for the user.

2) Composition of the retail price: For the commodity price in (2), two profiles are assumed. The first is a flat one, so $P = 1$. The second is a market profile with a value for every 15-minute interval, based on the 2008 Belpex profile. This second profile is used for comparison. An average value of 0.09 €/kWh is set for both profiles [30].

For the capacity part in (3), a system of subscription is assumed. The capacity is subscribed at the beginning of the period and cannot be exceeded. Otherwise supply is interrupted until demand is reduced. It is assumed that every of the 60 users subscribes the maximum value of its profile.

Three tariff designs are considered for the case study. All use one factor $c^{\text{Cap}}_{\text{Off}}$ for all time-slots j in

(3). They vary in the design of the components $c^{\text{En}}_{\text{Off},j}$. The design is similar to the system of French retail prices [31].

- Flat tariff with one factor $c^{\text{En}}_{\text{Off}}$.
- Time of use (ToU) tariff with a differentiation between peak and off-peak time. This leads to two factors $c^{\text{En}}_{\text{Off},(1,2)}$. Peak time is applied from 6:00 to 22:00.
- Critical peak pricing (CPP) tariff based on the ToU tariff. Additionally a differentiation is made for 22 critical peak days with the highest load, 43 peak days and 300 normal days. This leads to six factors $c^{\text{En}}_{\text{Off},(1-6)}$.

It is assumed that the grid component of the retail price and the grid tariff are equal.

3) Reflectivity of the bill: For the case study, the factor for losses according to (6) is calculated as the share of individual energy exchange compared to total energy exchange with the grid. This is done as there is no underlying grid to derive losses.

$$U^i_{\text{Loss}} = \mu \left(\frac{\sum_{t=1}^{T}(P^i_t)}{\sum_{t=1}^{T}(P_{t,P_t \geq 0})} \right) + (1-\mu) \left(\frac{\sum_{t=1}^{T}(P^i_t)}{\sum_{t=1}^{T}(P_{t,P_t < 0})} \right) \tag{26}$$

where $P_{t,P_t \geq 0}$ denotes time-steps with a positive system-load and $P_{t,P_t<0}$ denotes time-steps with a negative system-load. The weight μ is set to the share of the positive power-flow on total power-flow. Contribution to losses is, thus, separated according to the direction of the power-flow to avoid averaging out contribution to losses.

Values of (0.75, 0.15 and 0.1) times the costs derived in section IV-A7 are assigned to the three factors α_1 - α_3.

4) Energy conservation: To estimate the effect of isolation, SLPs for heat pumps are used. Such SLPs are provided by DSOs as a temperature related set of profiles together with a time series for average daily temperatures [32]. Curves are provided in the range from around -15°C to 15°C outside temperature. As the effect of insulation measures, an increase in experienced outside temperature of 2 K is assumed. Profiles in (11) are:

$$\boldsymbol{P}^i_{\mathrm{T}^0} = \boldsymbol{P}^i + \boldsymbol{P}^{\mathrm{SLP_{HP}}}_{\mathrm{T}^0} \qquad \boldsymbol{P}^i_{\mathrm{T}^0+2} = \boldsymbol{P}^i + \boldsymbol{P}^{\mathrm{SLP_{HP}}}_{\mathrm{T}^0+2} \tag{27}$$

5) Risk of the bill: To derive the variated load profile $\boldsymbol{P}^i_{\text{actual}}$, all initial values are multiplied with a scaling factor x.

$$P^i_{\text{actual},t} = P^i_t \cdot x_t \tag{28}$$

x_t is a normal distributed random variable with a mean of 1 a standard deviation of 0.2 and is limited to values between 0 and 2. Additionally, the maximum capacity is limited to the initial value as the subscribed power cannot be exceeded.

$$P^i_{\text{actual,max}} \leq P^i_{\text{max}} \tag{29}$$

6) Balance between professional and residential users: To simulate average residential and small professional users, the SLPs Res11 and Pro1 from ERDF, the French DSO, are used [33]. These are scaled to 5 MWh (Res) and 8 MWh (Pro) annual consumption. To estimate the respective subscribed power, the so-called Θ factors are defined. These factors are originally defined to estimate an average 30-minute meter reading from the subscribed power in case of missing readings. Now, the subscribed power is derived by dividing the average readings by the Θ factors.

For the scaling factor, it is set $\lambda = 1$.

7) constraints: Total costs that have to be recovered (R_{Grid}, (18)) are derived by multiplying the energy off-take for the 60 profiles with an assumed grid tariff of 0.1 €/kWh[4].

The maximum increase in grid fees through PV(K^i_{limit}, (22)) is derived by multiplying the generated energy with 0.01 €/kWh.

8) Optimization: The weights w_1 - w_4 are arbitrarily set in 0.2 steps. This leads to a total of 56 combinations for each optimization run. No fixed order for the different $c^{\text{En}}_{\text{Off},k}$ is applied. Optimization can result in a higher tariff for off-peak hours than for peak hours. Optimization is done in Matlab, using

[4]This is a relatively high value, in line with the Flemish tariffs [30].

CPLEX and the Yalmip toolbox [34].

B. Results

1) Relation of objectives: Results for the flat tariff and a flat commodity price show different combinations of $c_{\mathrm{Off}}^{\mathrm{Cap}}$ and $c_{\mathrm{Off}}^{\mathrm{En}}$ as optimal. This is depicted in Figure 2. Different objectives lead, thus, to different shares of energy and capacity part.

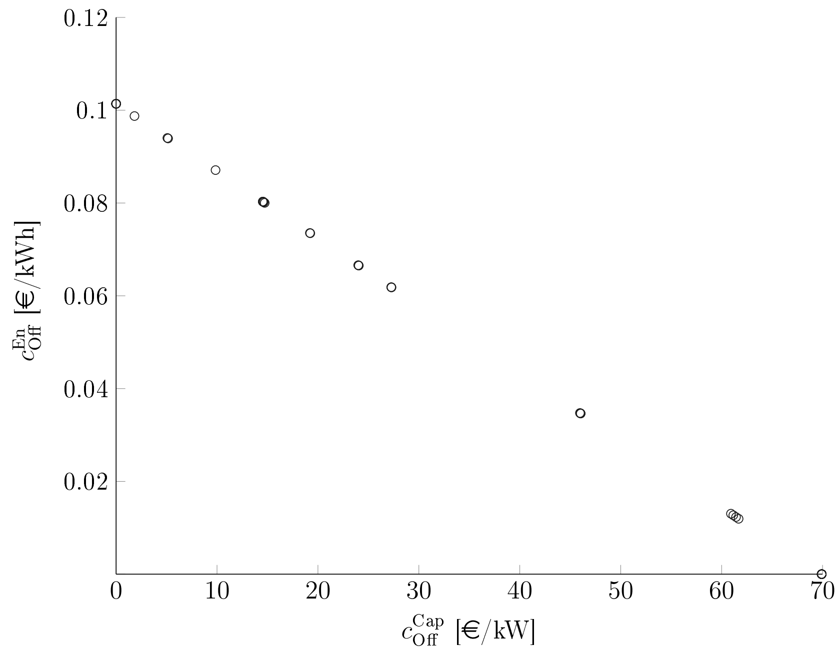

Fig. 2. Optimal tariff components for capacity and energy

For all four objectives, there is no dominant or dominated solution. If two objectives are considered separately, there are such solutions. As can be seen in Figure 3, there is a trade-off between different criteria For the objectives risk and balance between professional and residential users, Figure 3 indicates that there is just one optimal tariff. All other tariff combinations lead to worse results. For other criteria, for instance risk and gain, all tariff combinations form a Pareto front with no dominated solutions. For reflectivity and energy conservation, there is a small number of combinations that form a Pareto front while most combinations are dominated. In Figure 3, the dominated solutions are indicated for the objectives reflectivity and gain.

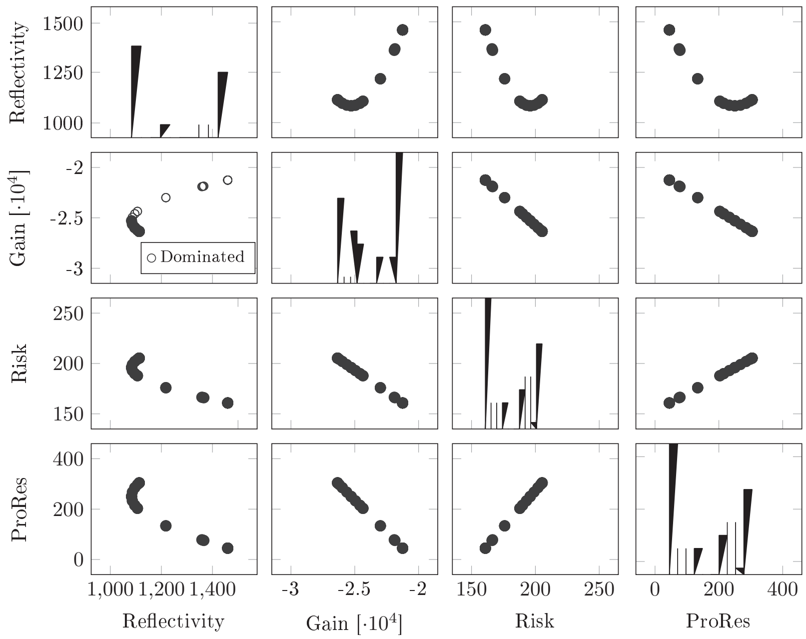

Fig. 3. Objective trade-off for flat tariff

2) Impact of local generation: As an example, Figure 4 depicts the Pareto fronts for reflectivity and gain from energy conservation for different PV levels. It can be seen that the front moves right to worse results. The front also becomes much longer so the variation between different solutions increases.

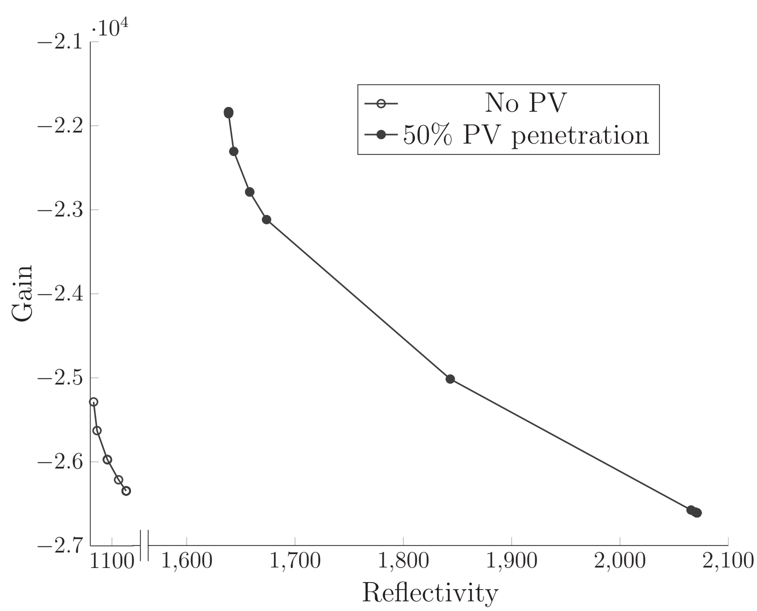

Fig. 4. Pareto fronts for different PV levels

3) Impact of different tariff designs: Tariffs with more control variable (time-slots) have a positive effect on the minimum values. In Figure 5, the relative minimum values for the three tariffs are displayed.

The CPP tariff has the lowest minima on all objectives. For reflectivity, the minimum with the flat tariff is around 17% higher. This is the biggest difference. For the balance between professional and residential users, there is no difference. The effect on the other objectives is in between. With higher PV penetration, the effect is reduced, especially for the reflectivity objective. With 50% penetration rate, the difference drops to 4.4%.

Also the trade-offs between the criteria are affected. Figure 6 shows the trade-off between reflectivity and gain from energy conservation. The increase in time-slots results in a move of the Pareto fronts in south western direction which is favorable. The Pareto fronts also become longer which offers more options for non-dominated tariff solutions. Visual analysis of the Pareto fronts reveals a bended form which leads to areas with low trade-off costs. In these areas, improving one objective requires only limited deterioration at the other. In Figure 6 this is indicated by dotted circles.

Cost of these tariffs with more time-slots is an increase in complexity. While the flat tariff has two components, the CPP tariff has already seven components.

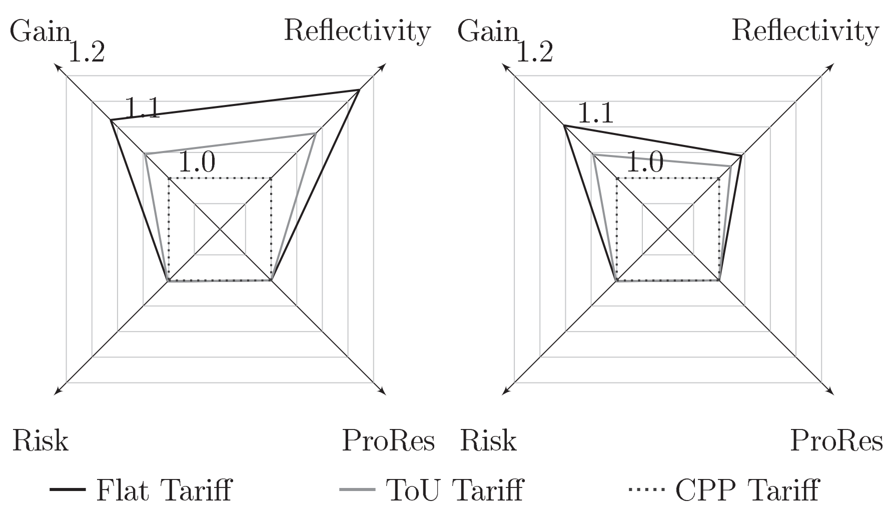

Fig. 5. Relative minimum values for different tariffs with no PV (left) and 50% PV penetration rate (right)

As a result of optimization, there are 56 solutions for each tariff and PV penetration level. Among these solutions there are many which are quite similar. If only those tariffs are counted, for which the capacity component, rounded to zero digits, differs, around 10 to 15 tariffs remain. For the flat tariff, on average 10.5 tariffs remain, for the CPP tariff on average 15.25 tariffs remain which is almost 50% more. For the

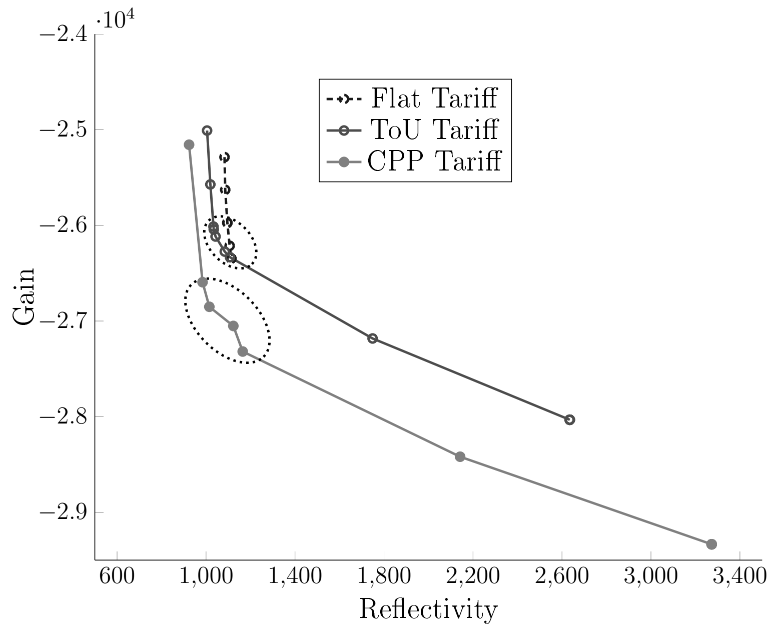

Fig. 6. Pareto fronts for different tariffs. Areas with low trade-off costs are indicated.

ToU tariff, on average 13 tariffs remain. With more flexibility on the energy component, obviously, there is more flexibility to fine tune the capacity component. These components evolve as depicted in Figure 7.

It can be seen that median capacity component for all tariffs is at a similar level of 20–22 €/kW. This median increases with rising PV penetration up to 57 €/kW while minimum and maximum values remain unaffected. For very high PV penetration the median capacity component drops back to low values. Main driver is the reflectivity objective. For rising PV levels, capacity is obviously a more reflective measure. Yet, for very high levels, this changes, again.

V. Conclusions

In this paper a multi-objective approach to LV grid tariff setting is proposed. The objectives include reflectivity, energy conservation, risk and the balance between professional and residential grid users. This is constrained by the revenue cap and limited impact on local generation. Such an approach is in line with energy policy which sets multiple objectives. The proposed framework translates these high level objectives into objectives that can be quantified.

The list of included objectives is not necessarily exhaustive. There might be additional objectives or

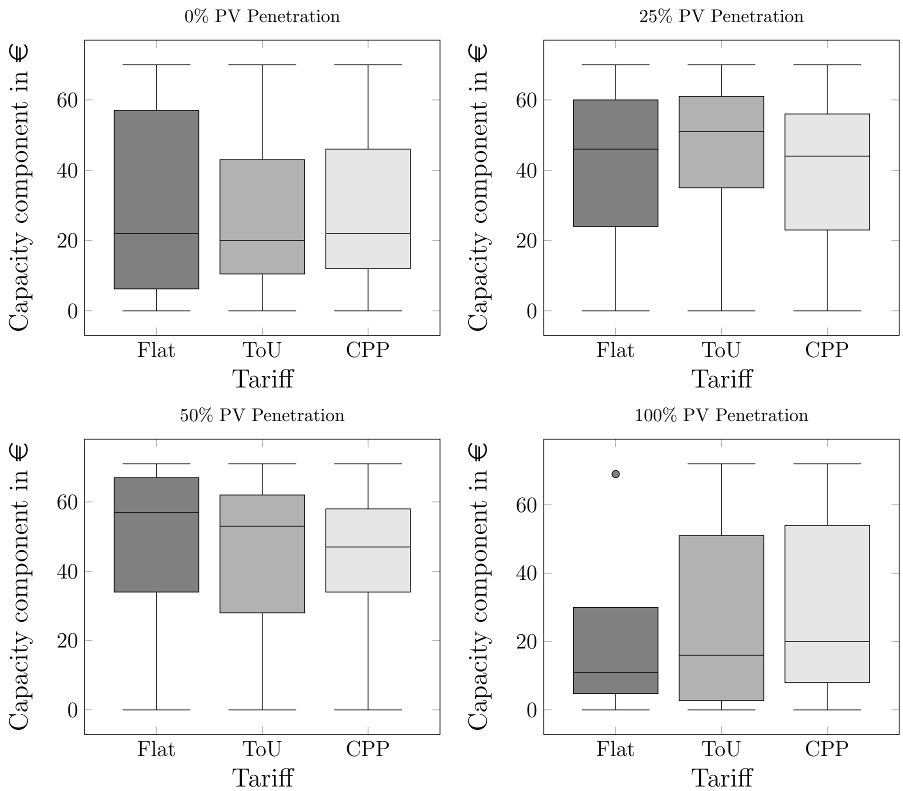

Fig. 7. Distribution of capacity component, depending on tariff and PV penetration. Distribution is depicted for the 10-15 different capacity components per tariff. Depicted are minimum and maximum, median and the interval between 0.75 percentile and 0.25 percentile. Minimum and maximum values which are outside the 0.75 to 0.25 interval ± 1.5 times the interval width are depicted with a dot.

constraints for instance for user groups such as electrical vehicles. It would also be an option to exchange constraints and objectives. The impact on PV-operators, for instance, could become an objective.

When designing a tariff the model can be used in many ways. Firstly, it can help to set optimal values for a given structure. Secondly, the model can be used to compare the impact of different structures. It can be used, for instance, to estimate the gain from using more time-slots. Then, it is possible to see the impact of different weights attached to the objectives. Finally, by using different tax structures and commodity price structures the model can help to make all parts of the retail price fit together.

For assigning the weights to the objectives, there are basically two ways. At first, they can be set based on fulfillment of political objectives. If investment in energy conservation is below targets, the respective weight could be raised. As a second option, the weights can be set arbitrarily, as in the case study. Then, the tariff can be designed based on the output. Though there is no dominant solution in the case study for all objectives, there are such solutions if only two objectives are selected. Additionally, as seen in

Figure 6, there are more favorable solutions among the efficient ones. All this should influence the tariff design.

The included case shows the trade-off between the different objectives if different weights attached to them. There is no optimal tariff which fulfills all aspects at once. Instead, there are several combinations of capacity component and energy component which are optimal for the respective weighting. This trade-off outlines the importance of considering multiple objectives for the tariff design. The user, for instance policy, has to define where to lay the focus on. Even if the weight of one or more of the proposed objectives is set to zero, there should be awareness for the cost related to such a decision. This leads to the conclusion for policy makers that they should do such a translation and quantification of their high level objectives. The proposed framework is a tool to do so.

A main aspect for further work is that the current system is closed. It is currently not considered how users react on tariffs and how this affects the objectives. Future work should model this reaction on tariffs to draw also conclusions about the impact on system costs. Such work closes the loop in Figure 1.

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